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Users' Description of JPL Ephemeris Tapes

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CONTENTS

TABLES

FIGURES

ACKNOWLEDGMENTS

Many people have contributed to the design and establishment of the Ephemeris Tape System. In particular, special acknowledgments must go to N. Block, whose reevaluations of the basic lunar and planetary theories via IBM 7094 computer programs constitute the source of the data carried in the system; to J. Devine, for transcription and editing of the Themis tapes and the decks of cards obtained from the U.S. Naval Observatory (USNO), and for the development of the IBM 7094 program PLOD; to H. Hudson and D. Holdridge, who assisted in the design of the present system; and to G. Clemence and R. Duncombe of the USNO, for their generous assistance and advice on many aspects of source data generation and numerical integration procedures.

ABSTRACT

A system for developing magnetic tape ephemerides of the Moon and the planets has been established at the Jet Propulsion Laboratory. Details pertinent to the distribution of these tapes and to their use in digital computer programs are given. In addition, the important features of the system relating to motivation, data acquisition and generation, ephemeris tape development, and procedures for assuring the accuracy of the data are described.

I. INTRODUCTION

Predictions of the motion of celestial bodies can be presented in either of two forms: as general but complicated formulas with time as argument, from which position at any epoch can be computed; or as tables listing positions at discrete, pre-specified epochs, from which positions at other than tabular epochs can be obtained by interpolation. These tables are called ephemerides. Predictions computed by a special perturbation method can, of course, be presented only in ephemeris form.

It has become customary to rely exclusively on ephemerides for astronomical work involving lunar and planetary motion, since the labor required for the preparation of an ephemeris can be allocated to the solution of many different problems. In recent decades the tasks of preparing and publishing lunar and planetary ephemerides have been shared by the Nautical Almanac Office of the U.S. Naval Observatory (USNO) and by its British counterpart, Her Majesty's Nautical Almanac Office. The Nautical Almanac Office of the USNO remains the official source of predictions of lunar and planetary motions for this country.

Until recent years ephemerides were used primarily for observational astronomy, time-keeping, geodetic surveys, and navigation. Both the accuracy of the published positions, amounting generally to 0.1 sec of arc in latitude and longitude (Ref. 1), and the pace of publication, in which a lead time of from 5 to 10 years is maintained, are satisfactory for these uses.

More severe requirements, however, are imposed on the accuracy and extent of ephemerides needed for the solution of problems associated with space exploration. Furthermore, these problems are invariably attacked with digital computer techniques, so that it is necessary to prepare ephemeris data in machine-acceptable form, primarily on magnetic tape.

A number of magnetic tape ephemerides have been developed from data furnished by the Nautical Almanac Office. The Jet Propulsion Laboratory (JPL) has in particular developed or shared in developing two such tape ephemerides, as described in Ref. 2 and Ref. 3, and has distributed copies of these tapes, as well as copies of the computer programs that use them, generally throughout the United States.

These tapes are no longer adequate for the solution of current problems at JPL, and they are being superseded by the new ephemeris system described in this Report.

In view of the many current investigations into the motion of the Moon and planets, no set of predicted motions now available can be considered final. Accordingly, the procedures, computer programs, and tape archives of ephemeris data that were used in preparing the new ephemerides have been collected into an operational system that will permit the issuing of updated ephemerides whenever a new issue is desirable and feasible. This system is called the JPL Ephemeris Tape System. The tapes issued under this system are called JPL Ephemeris Tapes.

While the JPL Ephemeris Tape System was established solely to meet JPL's needs, it is realized that the ephemeris tapes generated, and possibly the computer program used for interpolating the ephemerides, are useful to others.

This Report is intended to acquaint users of JPL Ephemeris Tapes with the details connected with the generation and use of these tapes. In particular, Part III, together with the Appendixes, constitutes a user's manual for the JPL Ephemeris Tapes. The remaining sections describe the major features of the new tapes, the general organization and operation of the system, the sources of ephemeris data acquired or generated, and the procedures for control, checking, and documentation.

II. FEATURES OF THE JPL EPHEMERIS TAPE SYSTEM

The JPL Ephemeris Tape System is a collection of procedures, IBM 7094 computer programs, and tape archives of ephemeris data used for generating JPL Ephemeris Tapes. These tapes may be used directly by digital computer programs that require predictions of lunar and planetary positions and velocities.

Input to the system consists of predictions of the positions of the Moon and planets obtained by any suitable means and recorded in simple format onto magnetic tapes. These tapes are preserved permanently in archives designated as the source tape library.

The ephemeris data available to users are recorded on a sequence of JPL Ephemeris Tapes. Each set of Ephemeris Tapes in the sequence consists of three tapes which collectively cover the years 1950–2000 with overlaps between tapes, and which carry tabulations of rectangular coordinates and velocity components of the Moon and the nine planets, plus nutations in longitude and obliquity, plus modified second and fourth differences of these quantities to facilitate interpolation. The format of the ephemeris tapes is defined in Appendix A.

A major innovation in the system is the provision of velocity as well as position predictions. It is recognized that numerical differentiation of tabulated positions is too inaccurate for problems in which planetary velocities are critical. For these critical cases, planetary position and velocity are simultaneously obtained from a special perturbation solution of the equations of motion for the planet. The IBM 7094 computer program that generates such special perturbation solutions, called PLOD for planetary orbit determination, is described in Part IV. The program generates position and velocity predictions that are mutually consistent with gravitational theory to high precision, and that are the best fit in the least-squares sense to source position predictions.

The aim of the JPL Ephemeris Tape System is to maintain ephemeris tapes containing the most accurate predictions of lunar and planetary motion available. The accuracy of the data published is limited by the accuracy of the source ephemeris data itself. At the present time the best source theory for the Moon is the Brown Improved Lunar Theory (Ref. 4). The Newcomb theories (Ref. 5, 6, 7) are used for Mercury, for Venus, and for the Earth–Moon barycenter, with corrections to the mean elements deduced for Mercury by G. Clemence (Ref. 8) and for Venus and the Earth–Moon barycenter by R. Duncombe (Ref. 9). The provisional Hansen–Clemence theory (Ref. 10, 11) is used for Mars. For the outer planets, the source data are obtained from the numerical integration by Eckert, Brouwer, and Clemence (Ref. 12), with corrections deduced by Clemence (Ref. 13) to transform the data to heliocentric coordinates.

Previous evaluations of the Brown Lunar Theory and of the Newcomb theories (Ref. 14, 15) have been limited in precision, primarily because of the use of tables instead of direct evaluation of the theories themselves. While these evaluations have been preserved in the source tape library, the preferred source data used in the JPL Ephemeris Tape System have been generated by IBM 7094 computer programs developed by N. Block (Ref. 16, 17, and 18). These evaluations have been carried out in double precision. The programs for evaluation of the Newcomb theories admit arbitrary corrections to the mean elements in the form $A + Bt$.

These programs, and others under development (but not actually part of the JPL Ephemeris System), will permit the application of further corrections obtained from current investigations of the motion of the Moon and inner planets, particularly corrections deduced by reduction of radar observations. Finally, new and more accurate theories of the motion of the Moon and planets are expected eventually, and evaluations of these theories will be assimilated into the JPL Ephemeris Tape System when they become available.

The JPL Ephemeris Tape System was designed to prevent degradation of the accuracy of source data during the data processing. The principal provisions for assuring the accuracy of the data include the following:

1. Positions and velocities are carried as double-precision floating point numbers (that is, to about 16 decimal places). Thus predictions more accurate than those now available can be assimilated into the Ephemeris Tape System.

2. Intervals of tabulation were chosen so that the use of Everett's interpolation formula retaining second and fourth modified differences yields sufficient accuracy.

3. Formal procedures for checking each step of the processing of ephemeris data have been instituted

in order to insure that the published ephemerides are free from human and mechanical error. These procedures are described in Part V.

The data in any set of three ephemeris tapes are complete over the years 1950–2000—in fact, they are generally more complete than any particular problem would require. These tapes are intended to supersede all other ephemeris tapes currently used at JPL, thereby eliminating the proliferation of various versions developed for use in different problems.

The interval 1950–2000 is adequate for the solution of most current problems. However, the system is designed so that ephemeris data for periods preceding 1950 or following 2000 can be provided easily and quickly, and can be used without revising any programs. In fact, source tapes for periods extending beyond 1950–2000 have already been generated.

Generation of a new set of JPL Ephemeris Tapes is only a question of data processing; no changes in the system or any of its programs are required. Revision of ephemeris tapes is simplified by maintaining tape libraries and system data-processing programs. Only a few weeks are required for the generation of a new set of ephemeris tapes, including full checking and documentation. Careful documentation of these tapes is required in order that questions concerning the origin, accuracy, and format of data can be answered quickly and correctly. This documentation is achieved by a system of internal memoranda by which the contents of each tape are identified. This identification is repeated, in part, on each tape.

III. EPHEMERIS TAPE USAGE

A sequence of sets of JPL Ephemeris Tapes, varying in content but not in format, is planned. This sequence is required in order to incorporate corrections to the source lunar and planetary theories; in addition, the extent of fitted position–velocity data will vary from one set to the next. Although revisions of one set of ephemeris tapes or replacements by the next set will not occur frequently, confusion about the contents of a particular set is prevented by the cross-referenced system of tapes and documents available to the user.

The items distributed to users, which are the only parts of the JPL Ephemeris Tape System of direct interest to them, are collected into a JPL Ephemeris Computer Package, which contains the following items:

1. This Report.
2. The ephemeris interpolation subroutine EPHEM, as a symbolic card deck. (This subroutine is described in Appendix B.)
3. A particular set of three JPL Ephemeris Tapes that carry the tabulation of data. (The format and general features of the contents of JPL Ephemeris Tapes are described in Appendix A.)
4. The corresponding tape document, in the form of a JPL Technical Memorandum, that describes the data of item 3 in detail. (Appendix A of this Report is repeated in each of the tape documents.)

The first two items are not changed by revision or replacement of the last two. The sets of ephemeris tapes, and the three tapes in each set (item 3), are given distinct alphanumerical names, which are repeated in the title of the relevant tape document. Conversely, enough of the information in the tape document is repeated in a label on each tape to permit positive identification. The tape document, item 4, is assembled from the internal memoranda that identify the various library tapes used for the development of the corresponding set of JPL Ephemeris Tapes. The tape document contains

1. Information about the theories used for the source data generation, with statements about the accuracy of each.
2. Definitions of coordinate systems, units, etc.
3. Information about the segments and quality of fit for the data obtained from PLOD, and the parameters and final elements by which the fitted data are defined.
4. Tape format, as in Appendix A of this Report.
5. References to reports that give more detailed information about source theory evaluations and PLOD fits.

The JPL Ephemeris Tapes are used at JPL to refresh a module of an IBM 1301 Disk File, called the Ephemeris Module, from which data are interpolated for the user programs. This usage requires the disk input/output portions of the JPL Space Flight Operations Facility Monitor Program, as well as a modified version of EPHEM and two additional programs: OMEGA, for refreshing the disk, and UNIVER, for obtaining the tables of physical constants needed by EPHEM and other programs from the disk. This usage is documented in Ref. 19.

IV. ORGANIZATION AND OPERATION OF THE EPHEMERIS TAPE SYSTEM

A. General Structure

While information about the internal structure of the Ephemeris Tape System is not necessary to the use of the JPL Ephemeris Tapes and programs, some facts about the techniques of data acquisition, documentation, and data verification may be useful.

The system consists of

1. *Tape libraries.* The archives of ephemeris data carried on magnetic tape are organized into four libraries: the source tape library, the position–velocity tape library, the merge tape library, and the final ephemeris tape library from which the sequence of ephemeris tapes distributed to users is taken.
2. *Computer programs.* Among the IBM 7094 programs included are those for generating velocity data from source position data; for processing data through various operations to obtain the final ephemeris tape; and for producing plots and lists and for checking consistency as a means of data verification. The routine EPHEM for interpolating the ephemeris tapes is also included.
3. *Documentation procedures.*

The system is operated by a manager who is one member of an ephemeris control board. The board has the responsibility for authorizing and defining the content of new ephemeris tapes, and for certifying their accuracy upon completion.

The entire system is documented in detail in a JPL Section Report (Ref. 19).

B. Tape Libraries and Data Flow

The flow of ephemeris data from the source through the various programs to final recording on an ephemeris tape is depicted in Fig. 1. This figure is explained in the following.

1. Source Data Generation

The basic data consist of predictions of lunar and planetary position and of the corresponding nutations in longitude and obliquity. These data are generated and/or edited by a number of IBM 7094 programs and are preserved in a simple format on magnetic tapes; these tapes constitute the source tape library. Check cases and comparisons with previous theories are provided to the ephemeris control board for the purpose of verifying the accuracy and consistency of the source data. Each of the tapes is completely documented on a standard form, which is shown in Appendix C. The form is repeated in part in a label on the tape itself. The present contents of the source tape library are defined in Table 1.

2. Velocity Data Generation

Position–velocity ephemerides are obtained from source position data in either of two ways:

1. Velocities are calculated by numerical differentiation of source positions, source positions remaining undisturbed.
2. Both position and velocity are obtained from a numerical solution of the equations of motion of a particular planet, with initial values differentially corrected so as to obtain the least-squares fit to the source data.

The program that performs the numerical differentiation is called SPEED and uses the derivative of Everett's interpolating polynomial with eighth differences retained. Nutation rates are calculated by the same technique. The program for the least-squares fitting of numerical integrations to source data is called PLOD. It is described more completely in Section IV-B-6.

Output from either PLOD or SPEED consists of a labeled magnetic tape that contains the position and velocity tabulations for a single body. If the interval covered by PLOD tapes is shorter than the required 1950–2000 interval, it is necessary to fill out the PLOD data with numerically differentiated velocities from SPEED. This is accomplished by the program SPLERG. The output tapes from SPEED, PLOD, and SPLERG together constitute the position–velocity, or PV, tape library. Each tape is documented in a standard form similar to the form used for source tape documentation; this document is generated automatically by PLOD for its output tapes and carries statistics as to the fit along with other information. The information is repeated in part in the label on each tape.

3. Data Processing

A particular verision of the set of three ephemeris tapes available to users is obtained from a selection of PV tapes via a series of data-processing programs, as follows:

1. Modified second and fourth central differences (that is, with throwbacks of sixth and eighth differences) are calculated by the program PVDIF, and a labeled output tape carrying position and velocity tabulations and their modified differences is written. Only data for one body appear on a particular tape.

2. The new one-body tape is combined, by the program MERGE, with the previously obtained n-body merge tape to obtain an $(n+1)$-body merge tape. Since many of the data carried in a new issue of ephemeris tapes will be the same as in the previous issue, it is convenient to preserve previous merge tapes in a merge tape library. This library is organized only for the convenience of the manager and is documented by him only for his own needs. Any merge tape can be recovered from the appropriate PV tapes if necessary.

3. The final ten-body merged data, now consisting of three tapes that carry the ephemeris data for all the bodies over the full 50-year interval, are overlapped and buffered into the final three-tape JPL Ephemeris Tapes by the program BUFF. Copies of these tapes are distributed to users.

4. Interpolation Program

The user program EPHEM is described in Appendix B. Note that positions of the perturbing planets, necessary for calculating the perturbing accelerations of a given planet in the program PLOD, are obtained from the Ephemeris Tapes via EPHEM.

5. Data Verification

The procedures for verifying that the generation and transcription of data have proceeded without error are a vital feature of the Ephemeris Tape System. The verification procedures for which the ephemeris control board is responsible include the following:

1. Check cases and comparisons with previous evaluations of source theories are examined to insure the correctness of data generation.

2. Plots and/or lists of position–velocity data and of their sixth differences are tested for transcription errors in source and PV tapes. These plots and lists are obtained by the program PLIST.

3. The statistical summary from PLOD and plots and/or lists of residuals in rectangular position and velocity and in ecliptic latitude, longitude, and radius vector in the sense (source minus PLOD) are processed by PLIST.

4. A consistency check is made between the final position and velocity data carried on the master ephemeris tapes and on the pertinent PV tapes, using the program CONCHK. The record-to-record and tape-to-tape overlaps are also checked by this program.

5. A check of the modified differences carried on the JPL Ephemeris Tapes, EPHEM is used to write a tape carrying the positions and velocities of a given body at the midpoints of its tabulated dates; the appropriate program is called DIFCHK. These tapes are then processed by PLIST to check sixth differences for smoothness.

6. Description of PLOD

The program PLOD, described in detail in Ref. 20, has been designed so as to improve certain features in previous fits to ephemeris data reported in Ref. 21. The program consists essentially of two parts: numerical integration of the equations of motion for a specified planet, starting at a specified epoch T_0 with an estimate of osculating ecliptic elliptic elements of the planet at that epoch; and a linear regression scheme that generates and applies differential corrections to the osculating elements at the epoch T_0 until the least-squares fit to the given source data is obtained.

The equations of motion are integrated in a heliocentric equatorial rectangular frame, using a Cowell second-sum predictor–corrector and retaining eighth differences. Position and velocity at the epoch T_0 are, of course, obtained from the osculating elements at T_0, using the obliquity of 1950.0. Starting values for the Cowell integration are obtained from similar quadrature formulas, also retaining eighth differences. All computations are carried to at least double precision; that is, to about sixteen figures. The perturbing attractions of the other eight planets are computed from positions obtained via EPHEM from the current Ephemeris Tape. The integration step size is chosen so as to insure twelve-figure

accuracy in the calculated positions. Residuals in ecliptic latitude and longitude, and the corresponding regression coefficients, are computed at each of a set of epochs included in the range of integration in order to form equations of condition. These are accumulated into normal equations, which are solved at the end of the integration for the differential corrections to the osculating elements at T_0. The solutions of the normal equations are monitored to insure the statistical significance of the calculated corrections. The corrections are applied and the process is repeated until convergence; that is, until no further significant reduction in the sum of squares of residuals is possible. The final corrected values of the osculating elements at T_0 are then used to initiate a final numerical integration, during which the position–velocity output tape is written.

Osculating elliptic elements at T_0 rather than rectangular position and velocity were chosen as the parameters defining the orbit, in order to improve the conditioning of the normal matrix. The usual Keplerian elements are used with the single exception of replacing the argument of perihelion with the longitude of perihelion. This avoids difficulty caused by zero inclination, which may appear in the process of fitting the Earth–Moon barycenter. Residuals in latitude and longitude were chosen as the basis for fitting in order to reconcile apparent inconsistency between the scale and period of the source orbit, as disclosed in the residuals published in Ref. 21. Plots of residuals in ecliptic latitude and longitude no longer show periodic components with the sidereal period of the planets. These periodic components still appear in the residuals in the radius vector, of course, and therefore in the residuals in rectangular coordinates.

Finally, it was decided to perform the regression in the ecliptic, rather than the equatorial, frame, even though the integration is in the equatorial frame, in order to obtain a better separation of the effects of changes in parameters upon residuals.

V. DATA QUALITY ASSURANCE AND DOCUMENTATION

Since many numbers are processed in order to produce a set of three JPL Ephemeris Tapes, it is necessary to include in the JPL Ephemeris System several check points to insure the quality of the data. These check points each involve computer programs. These programs in general present graphical information from which one can determine whether the data have been processed correctly.

The source positions generated by computer programs were checked as follows: The evaluations of the theories of Venus and the Earth–Moon barycenter were checked by computing and plotting residuals of the JPL-generated values minus the Herget evaluation recorded on the Themis tapes (Ref. 17, 18). A sample residual plot is shown in Fig. 2. In the case of Mercury, the residuals of JPL-computed values minus values from USNO cards were plotted (Ref. 5). Mars data on the current tapes were not generated at JPL and therefore were not checked by residual plots at the source level. The coordinates of the outer planets were checked by plotting residuals of the corrected values minus the source values (Ref. 12, 13). The coordinates of the Moon were checked by plotting residuals of the JPL-generated values minus the USNO data as modified for JPL–STL Ephemeris Tapes (Ref. 2). The lunar residuals are shown in Fig. 3. An additional check on the lunar coordinates was made by computing residuals of the JPL values minus the values published by Duncombe (Ref. 4).

In addition, all source data are checked for consistency by generating and plotting sixth-order central differences (Fig. 4). Sixth differences are also plotted for all PLOD-fitted data, and velocities are checked as well as positions. Also, residuals of source data minus fitted data are computed and plotted to check the fitted data for consistency.

The next point where a consistency check is made is after all the data have been merged and buffered into the final JPL Ephemeris Tapes. The data for each body on the final tapes are compared with the corresponding data on the single-body position–velocity tapes and non-zero values are recorded. The JPL Ephemeris Tapes have redundant data between records and across tapes for ease of interpolation, and these overlapped regions are also checked in this comparison.

The only data remaining to be checked are the modified differences. These are checked by using them to generate a single-body position–velocity tape which is off-set from the original data by one half of the tabulation interval for that body. Sixth-order central differences are generated and plotted from this tape, and these differences are then compared visually with the original central differences for that body.

Check sums are computed and recorded on the final JPL Ephemeris Tapes. This produces another check when reading from these tapes. It also allows for a reasonably good consistency check when reading the data back in from disk.

Table 1. Contents of the source tape library

Body	Interval	Step, days	Source theory and comments
Moon	1850–2000	0.5	Brown Improved Lunar Theory, DP[a] 7090 evaluation (Block), with nutations. (Total of 6 tapes, 1950–1978 on single tape.)
Mercury	1960–1981	2.0	Newcomb tables, SP[b] evaluation at USNO, cards processed by Devine
	1950–2000	2.0	Newcomb theory, DP[a] 7094 evaluation (Block)
	1950–2000	2.0	Same, with corrections to mean elements in form $A + Bt$ as deduced by Clemence
Venus	1950–2000	4.0	Newcomb tables, with correction of $4''.78T$ to Earth mean longitude, SP[b] evaluation by Herget, transcribed to Themis tapes at Livermore Radiation Lab., edited by Devine
Earth–Moon	1950–2000	4.0	Newcomb theory, DP[a] 7094 evaluation (Block), with same correction
	1950–2000	4.0	Same for Earth–Moon, without above correction
	1950–2000	4.0	Same, with Duncombe corrections to mean elements in form $A + Bt$
Mars	1950–2000	4.0	Hansen–Clemence provisional theory, SP[b] evaluation at USNO, cards processed by Devine
Outer planets	1950–2000	4.0	Numerical integration, transcribed to Themis tape at L.R.L., edited by Devine
	1950–2000	4.0	Same, with corrections for perturbations of inner planets on outer planets, via 7094 program (Block)

[a]DP = double precision
[b]SP = single precision

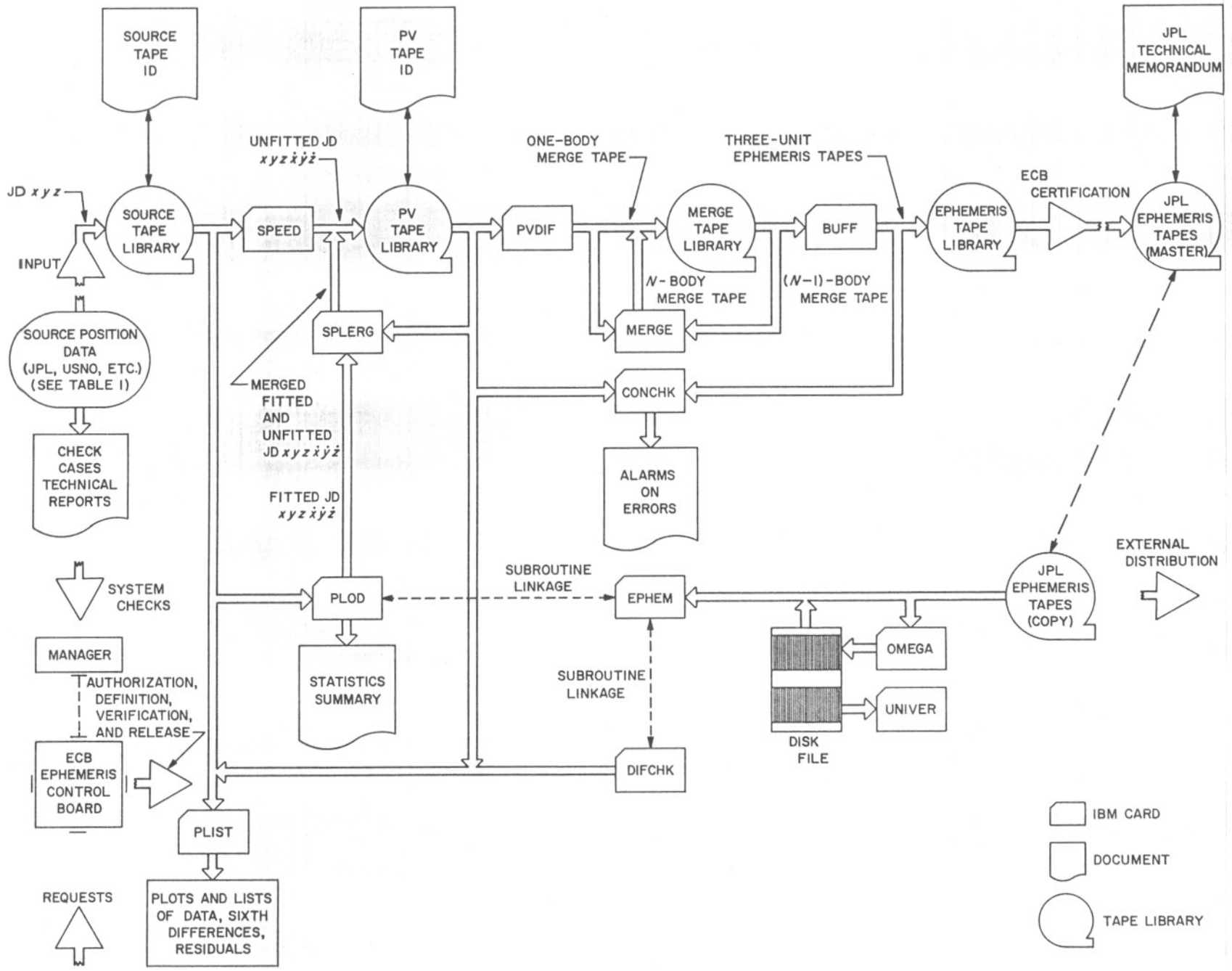

Fig. 1. JPL Ephemeris Tape System

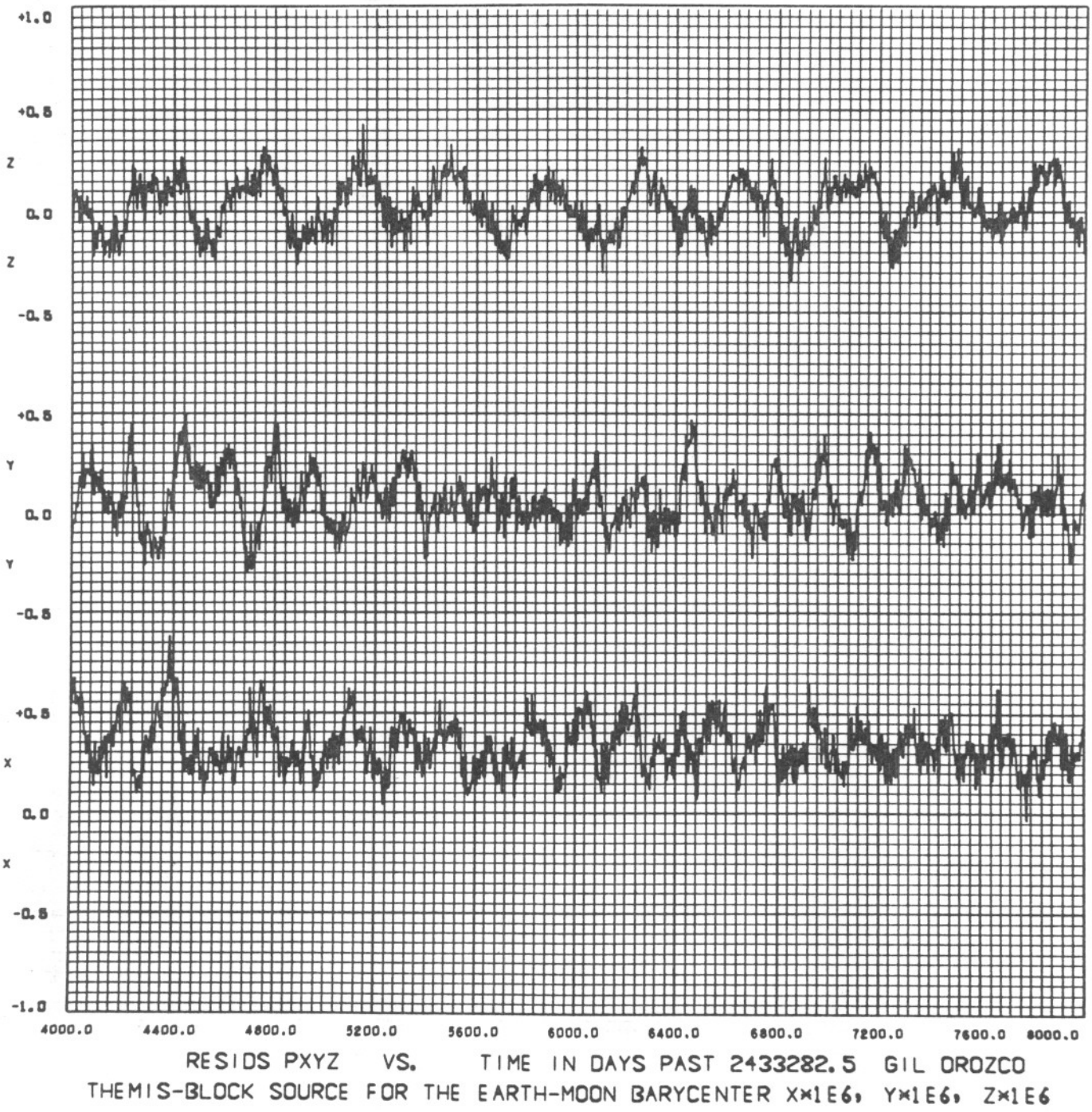

Fig. 2. Plotted residuals of IBM 7094 Newcomb theory evaluation minus Herget's evaluation from Themis tapes for the Earth–Moon barycenter

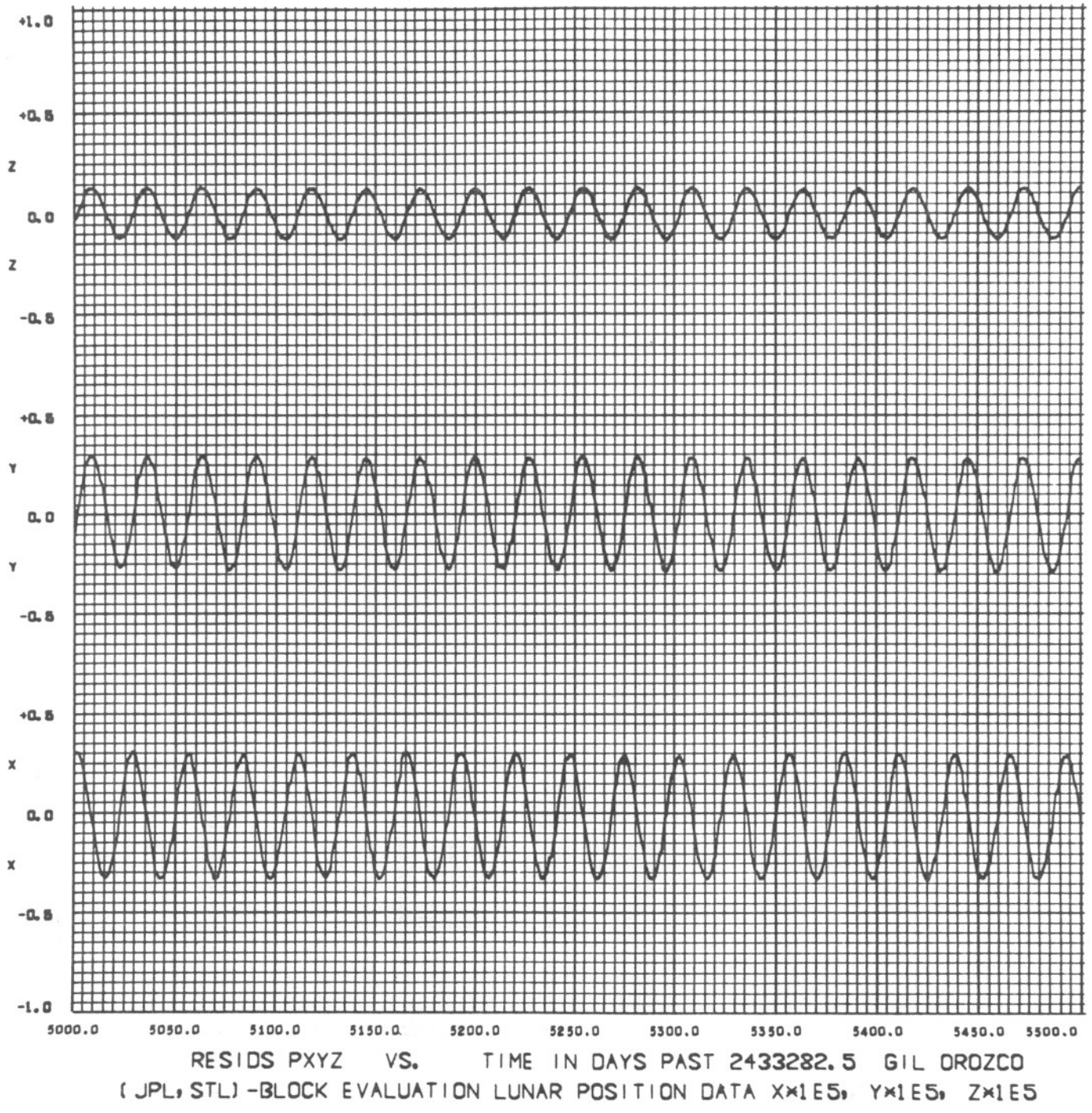

Fig. 3. Lunar residuals of JPL Brown Improved Theory minus USNO data as modified for JPL–STL Ephemeris Tapes

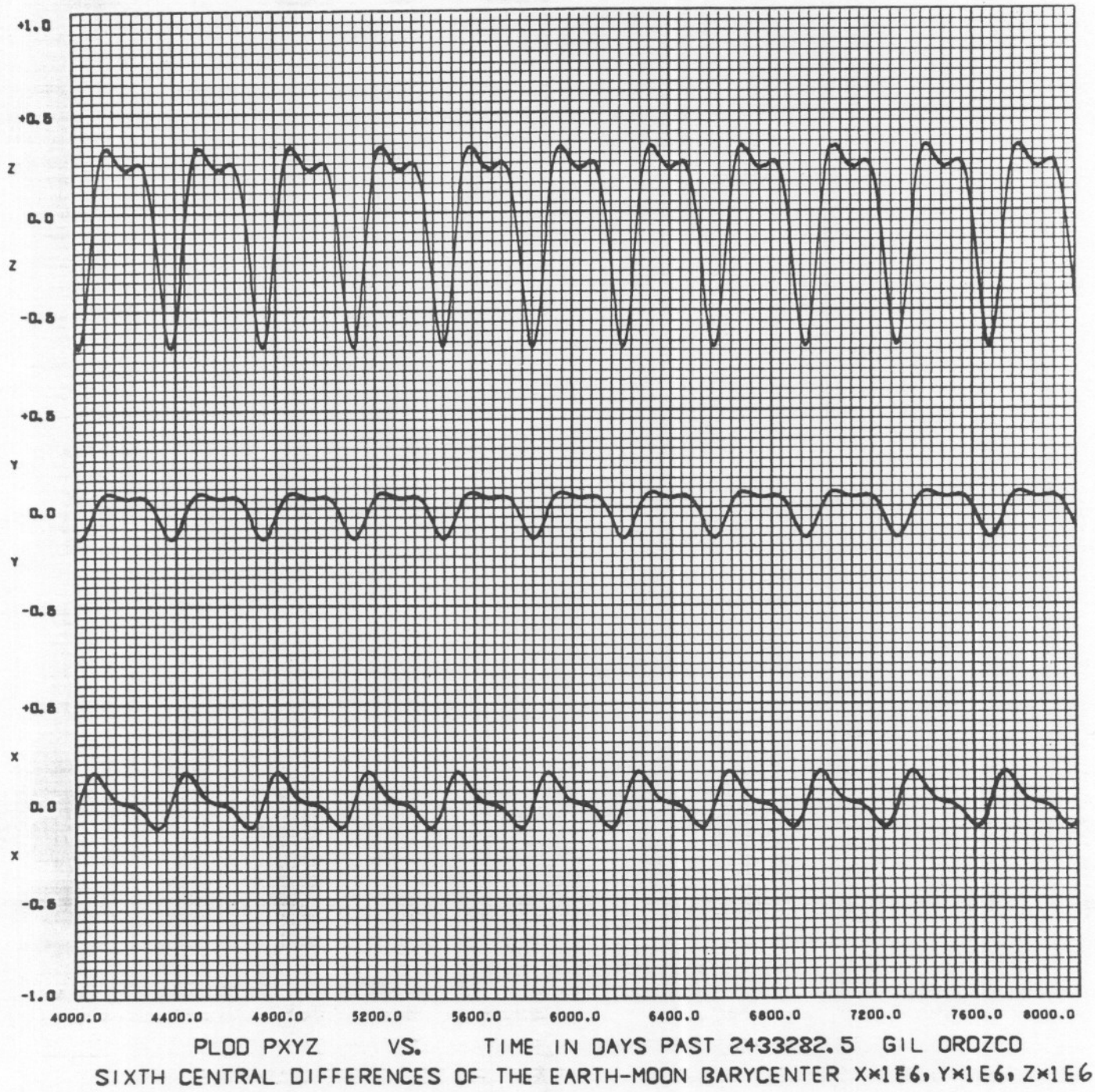

Fig. 4. Earth–Moon barycenter's sixth central differences

REFERENCES

1. Duncombe, R. L., "The Planetary Ephemerides," paper presented at SIAM, Monterey, California, April 21, 1961.

2. Hudson, R. H., *Subtabulated Lunar and Planetary Ephemerides,* Technical Release No. 34-239, Jet Propulsion Laboratory, Pasadena, California, November 2, 1960.

3. Holdridge, D. B., *Space Trajectories Program for the IBM 7090 Computer,* Technical Report No. 32-223, Jet Propulsion Laboratory, Pasadena, California, March 2, 1962.

4. *Improved Lunar Ephemeris, 1952–1959* (Prepared Jointly by the Nautical Almanac Offices of the USA and U.K.), U.S. Government Printing Office, Washington, D. C., 1954.

5. Newcomb, S., "Tables of the Heliocentric Motion of Mercury," *Astronomical Papers of the American Ephemeris,* Vol. VI, Pt. II, Nautical Almanac Office, U.S. Naval Observatory, U.S. Government Printing Office, Washington, D. C., 1898.

6. Newcomb, S., "Tables of the Heliocentric Motion of Venus," *Astronomical Papers of the American Ephemeris,* Vol. VI, Pt. III, Nautical Almanac Office, U.S. Naval Observatory, U.S. Government Printing Office, Washington, D. C., 1898.

7. Newcomb, S., "Tables of the Motion of the Earth on its Axis and Around the Sun," *Astronomical Papers of the American Ephemeris,* Vol. VI, Pt. I, Nautical Almanac Office, U.S. Naval Observatory, U.S. Government Printing Office, Washington, D. C., 1898.

8. Clemence, G. M., "The Motion of Mercury, 1765–1937," *Astronomical Papers of the American Ephemeris,* Vol. XI, Pt. I, Nautical Almanac Office, U.S. Naval Observatory, U.S. Government Printing Office, Washington, D. C., 1943.

9. Duncombe, R. L., "Motion of Venus," *Astronomical Papers of the American Ephemeris,* Vol. XVI, Pt. I, Nautical Almanac Office, U.S. Naval Observatory, U.S. Government Printing Office, Washington, D. C., 1958.

10. Clemence, G. M., "First-Order Theory of Mars," *Astronomical Papers of the American Ephemeris,* Vol. XI, Pt. II, Nautical Almanac Office, U.S. Naval Observatory, U.S. Government Printing Office, Washington, D. C., 1949.

11. Clemence, G. M., "Theory of Mars-Completion," *Astronomical Papers of the American Ephemeris,* Vol. XVI, Pt. II, Nautical Almanac Office, U.S. Naval Observatory, U.S. Government Printing Office, Washington, D. C., 1962.

12. Eckert, W. J., Brouwer, D., and Clemence, G. M., "Coordinates of the Five Outer Planets, 1653–2060," *Astronomical Papers of the American Ephemeris,* Vol. XII, Nautical Almanac Office, U.S. Naval Observatory, U.S. Government Printing Office, Washington, D. C., 1951.

13. Clemence, G. M., "Perturbations of the Five Outer Planets by the Four Inner Ones," *Astronomical Papers of the American Ephemeris,* Vol. XIII, Pt. V, Nautical Almanac Office, U.S. Naval Observatory, U.S. Government Printing Office, Washington, D. C., 1954.

14. Herget, P., "Solar Coordinates," *Astronomical Papers of the American Ephemeris,* Vol. XIV, Nautical Almanac Office, U.S. Naval Observatory, U.S. Government Printing Office, Washington, D. C., 1953.

REFERENCES (Cont'd)

15. Herget, P., "Coordinates of Venus," *Astronomical Papers of the American Ephemeris,* Vol. XV, Pt. III, Nautical Almanac Office, U.S. Naval Observatory, U.S. Government Printing Office, Washington, D.C., 1955.

16. Block, N., *The Brown Improved Lunar Theory,* Technical Report No. 32-590, Jet Propulsion Laboratory, Pasadena, California, to be published.

17. Block, N., *Ephemerides of Mercury, Venus, and Earth–Moon Barycentre, Evaluated from Newcomb's Theories,* Technical Report No. 32-591, Jet Propulsion Laboratory, Pasadena, California, to be published.

18. Block, N., *Heliocentric Coordinates of the Five Outer Planets,* Technical Report No. 32-592, Jet Propulsion Laboratory, Pasadena, California, to be published.

19. Orozco, E. G., *The JPL Ephemeris Tape System,* Section Report No. 372-12, Jet Propulsion Laboratory, Pasadena, California, March 2, 1964.

20. Devine, C. J., *An IBM 7094 Program for Orbit Filling by Numerical Integration,* Section Report No. 372-13, Jet Propulsion Laboratory, Pasadena, California, to be published.

21. Peabody, P., and Block, N., "Planetary Position–Velocity Ephemerides Obtained by Special Perturbations," *AIAA Journal,* Vol. 1, No. 12, December, 1963, pp. 2812–2815.

22. Clarke, V. C., Jr., *Constants and Related Data, (Revision No. 1),* Technical Report No. 32-273, Jet Propulsion Laboratory, Pasadena, California, March 6, 1964.

23. Clarke, V. C., Jr., "Earth Radius/Kilometer Conversion Factor for the Lunar Ephemeris," *AIAA Journal,* to be published.

APPENDIX A

JPL Ephemeris Tape Format

The same format is used for all JPL Ephemeris Tapes: two information records at the beginning of each tape followed by the data records. The record format may be described as follows:

A. The first record of each tape contains 24 BCD words written in binary. These 24 words serve to describe the general nature of the information on the tape.

B. The second record of each tape contains the following information in the order listed:

1. Number of bodies on tapes = 10.
2. A floating point 50., which denotes a buffered tape.
3. Initial Julian date for which data are provided.
4. Final Julian date for which data are provided.
5. Step size of the logical data record = 8.0 days.

6–25. Ten pairs of numbers. The first number of the pair denotes the body in increasing order out from the Sun, with a zero used for lunar data. The second number of each pair is the step size of data provided for that body.

C. The JPL Ephemeris Tapes contain data in buffered and overlapped 8-day logical records. The end points of the 8-day span are repeated as the first points of the succeeding 8-day record. This format allows ease of handling by the interpolation program.

The format for the JPL Ephemeris Tape records is listed in Table A-1. All data, with the exception of those for nutations, are double precision, so that the total record size is 1863 words. The step size for lunar data and nutations is one-half day. Mercury data are given in 2-day steps, and all other data, in 4-day steps.

Table A-1. Ephemeris tape record format

Word in record	Data
0	Julian date
2	Mercury: $X, \Delta^2_m X, \Delta^4_m X, Y, \Delta^2_m Y, \Delta^4_m Y, Z, \Delta^2_m Z, \Delta^4_m Z$ Followed by four more position data points $\dot{X}, \Delta^2_m \dot{X}, \Delta^4_m \dot{X}, \dot{Y}, \Delta^2_m \dot{Y}, \Delta^4_m \dot{Y}, \dot{Z}, \Delta^2_m \dot{Z}, \Delta^4_m \dot{Z}$ Followed by four more velocity data points
182	Venus: $X, \Delta^2_m X, \Delta^4_m X, Y, \Delta^2_m Y, \Delta^4_m Y, Z, \Delta^2_m Z, \Delta^4_m Z$ Followed by two more position data points $\dot{X}, \Delta^2_m \dot{X}, \Delta^4_m \dot{X}, \dot{Y}, \Delta^2_m \dot{Y}, \Delta^4_m \dot{Y}, \dot{Z}, \Delta^2_m \dot{Z}, \Delta^4_m \dot{Z}$ Followed by two more velocity data points
290	Earth–Moon barycenter: Same as Venus
398	Mars: Same as Venus
506	Jupiter: Same as Venus
614	Saturn: Same as Venus
722	Uranus: Same as Venus
830	Neptune: Same as Venus
938	Pluto: Same as Venus
1046	Moon: $X, \Delta^2_m X, \Delta^4_m X, Y, \Delta^2_m Y, \Delta^4_m Y, Z, \Delta^2_m Z, \Delta^4_m Z$ Followed by sixteen more position data points $\dot{X}, \Delta^2_m \dot{X}, \Delta^4_m \dot{X}, \dot{Y}, \Delta^2_m \dot{Y}, \Delta^4_m \dot{Y}, \dot{Z}, \Delta^2_m \dot{Z}, \Delta^4_m \dot{Z}$ Followed by sixteen more velocity data points
1658	Nutations: $\delta\Psi, \Delta^2_m \delta\Psi, \Delta^4_m \delta\Psi, \delta\varepsilon, \Delta^2_m \delta\varepsilon, \Delta^4_m \delta\varepsilon$ Followed by sixteen more nutation data points $\dot{\delta\Psi}, \Delta^2_m \dot{\delta\Psi}, \Delta^4_m \dot{\delta\Psi}, \dot{\delta\varepsilon}, \Delta^2_m \dot{\delta\varepsilon}, \Delta^4_m \dot{\delta\varepsilon}$ Followed by sixteen more nutation rate data points
1862	Check sum

The Julian date is the epoch (Ephemeris Time, ET) of the start of the data record. Lunar positions and velocities are referred to the geocentric equatorial rectangular reference frame of the mean equator and equinox of 1950.0 = JD 243 3282.423. They are expressed in units called "Earth radii" and "Earth radii"/mean solar day. Planetary positions and velocities are referred to the heliocentric equatorial rectangular frames of 1950.0, and are expressed in units of AU and AU/mean solar day.

The conversion of position and velocity tabulations to laboratory units, such as kilometers and kilometers per second, requires scaling by the conversion factors kilometers/AU and kilometers/"Earth radius." Conversion of

planetary data from a heliocentric to a geocentric frame of reference requires specification of the Earth–Moon mass ratio μ, in order to locate the Earth–Moon barycenter in the geocentric frame. Finally, if data are required for a particular epoch in Universal Time (UT), the time correction Δt_q = ET − UT must be specified.

In particular, the Brown Improved Lunar Theory is based upon values of ratios of solar to lunar parallax and of the Earth–Moon mass that are no longer considered the best estimates of these quantities. Thus, use of a best estimate of the actual value of the "Earth radius" in kilometers will not yield best estimates of the position of the Moon in kilometers, and an artificial value of the "Earth radius" is preferred for the scaling referred to above. Derivation of the value of the "Earth radius" to be used is given in Ref. 16 and Ref. 23. A consistent set of constants, and the set used at JPL, is given in Ref. 22. The ones pertinent to usage of JPL Ephemeris Tapes are

1 AU = 149599000 km

1 "Earth radius" = 6378.3255 km

and

μ = Earth/Moon mass ratio = 81.3015

The listed Earth/Moon mass ratio corresponds to

$$GM_e = 398603.2 \text{ km}^3/\text{sec}^2$$

and

$$GM_m = 4902.7779 \text{ km}^3/\text{sec}^2$$

APPENDIX B

Ephemeris Interpolation

I. INTRODUCTION

The ephemeris interpolation routine EPHEM is designed to read a JPL Ephemeris Tape and to interpolate for the position and/or velocity of any subset of the planets and Moon at any Julian date within the time interval spanned by the tape.

The ephemeris data carried on tape are in heliocentric coordinates for the planets and geocentric coordinates for the Moon. EPHEM, however, may be used to obtain coordinates referenced to any of the bodies as center. In particular, data are furnished for the Earth–Moon barycenter rather than for the Earth, and EPHEM performs the necessary calculations for obtaining geocentric coordinates of the planets and Sun.

II. METHOD

Everett's formula

$$x(T_j) = ux_0 + tx_1 + \frac{u(u^2-1)}{3!}\Delta_m^2 x_0 + \frac{t(t^2-1)}{3!}\Delta_m^2 x_1 + \frac{u(u^2-1)(u^2-4)}{5!}\Delta_m^4 x_1 + \frac{t(t^2-1)(t^2-4)}{5!}\Delta_m^4 x_1$$

is used for interpolation, where

T_j = the desired Julian date, $T \leq T_j < T + h$

h = step size of data

T = point in time at which data are tabulated

$t = (T_j - T)/h$, $0 \leq t \leq 1$

$u = 1 - t$

$x_0 = x(T)$

$x_1 = x(T + h)$

Δ_m^n = nth modified difference

It is assumed that the Julian date specified by the user as the epoch for which data are requested is in Universal Time. Since the ephemerides are tabulated in Ephemeris Time, the specified epoch is modified by

$$ET = UT + \Delta t$$

to convert to Ephemeris Time.

Planetary coordinates for centers other than the Sun are obtained by the vector subtraction

$$\mathbf{P} = \mathbf{P}_0 - \mathbf{C}$$

where

$\mathbf{P}$ = planetary coordinates referred to the desired center

$\mathbf{P}_0$ = planetary coordinates referred to the Sun

$\mathbf{C}$ = heliocentric coordinates of the desired center

A similar vector subtraction is performed for velocity vectors.

Calculation of the heliocentric coordinates of the Earth and/or Moon or the geocentric or selenocentric coordinates of the Sun and planets requires additional manipulations. Heliocentric lunar and Earth coordinates are obtained as

$$\mathbf{M} = \mathbf{B} + \mu_m \mathbf{L}$$

$$\mathbf{E} = \mathbf{B} + \mu_e \mathbf{L}$$

where

$\mathbf{M}$ = heliocentric coordinates of the Moon

$\mathbf{E}$ = heliocentric coordinates of the Earth

$\mathbf{B}$ = heliocentric coordinates of the Earth–Moon barycenter

$\mathbf{L}$ = geocentric coordinates of the Moon

$$\mu_m = \frac{\mu_E}{\mu_E + \mu_M}$$

$$\mu_e = \frac{\mu_M}{\mu_E + \mu_M}$$

μ_E = the GM of the Earth

and

μ_M = the GM of the Moon

Both μ_E and μ_M are obtained from TAB1, as described in Part III of this Appendix.

III. USAGE

The subroutine EPHEM may be used by either the FORTRAN II or the FAP programs. The calling sequence for a FORTRAN II program is

```
CALL EPHEM (JD, CENTER, TAB1, TAB2,
TAB3, TAB4, NTAPE)
```

and for the FAP program is

```
CALL EPHEM, JD, CENTER, TAB1, TAB2,
TAB3, TAB4, NTAPE
```

The arguments in the calling sequence are interpreted as follows:

JD = double-precision floating point Julian date T_j, assumed to be in Universal Time, at which data are required

CENTER = control-word floating integer identifying the desired center of the coordinate system according to the scheme given in Table B-1

TAB1 = 36-word table of physical constants with the structure given in Table B-2

TAB2 = 13 floating point integers that control the data output for each body according to the scheme given in Table B-3. The control-word sequence is given in Table B-4.

TAB3 = 1862-word buffer used by EPHEM to store a record of ephemeris data as it is read from the Ephemeris Tape

TAB4 = 150-word block of storage containing the output information listed in Table B-5. The control-word integer in TAB4 is interpreted as shown in Table B-6.

Table B-1. Central body identification

Body	Control integer	Body	Control integer
Mercury	1.0	Neptune	8.0
Venus	2.0	Pluto	9.0
Earth	3.0	Sun	10.0
Mars	4.0	Moon	11.0
Jupiter	5.0	Earth–Moon barycenter	12.0
Saturn	6.0		
Uranus	7.0		

Table B-2. TAB1 structure

Word in record	Physical constant and unit	Word format
TAB1	k = universal gravitational constant, $AU^{3/2}$/day	Double-precision floating point
+2	GM of Mercury, km^3/sec^2	
+4	GM of Venus, km^3/sec^2	
+6	GM of Earth, km^3/sec^2	
+8	GM of Mars, km^3/sec^2	
+10	GM of Jupiter, km^3/sec^2	
+12	GM of Saturn, km^3/sec^2	
+14	GM of Uranus, km^3/sec^2	
+16	GM of Neptune, km^3/sec^2	
+18	GM of Pluto, km^3/sec^2	
+20	GM of Sun, km^3/sec^2	
+22	GM of Moon, km^3/sec^2	
+24	Astronomical unit, km	
+26	Earth radius for lunar ephemeris conversion, km	
+28	Speed of light, km/sec	
+30	Solar-flux constant, lb-force/m^2	
+32	Seconds per mean solar day	
+34	Output-unit control word[a]	Single-precision floating point
+35	Δt = UT − ET, sec	Single-precision floating point

[a] If the output-unit control word is 0, the output is in km and km/sec; if it is 1.0, planetary data are in AU and AU/day and lunar data in "Earth radii" and "Earth radii"/day.

Table B-3. TAB2 output control interpretation

Control word	Meaning
0.	No data, this body
1.	Position data only, this body
2.	Velocity data only, this body
3.	Both position and velocity data, this body

Table B-4. TAB2 structure

Word position	Body controlled	Word position	Body controlled
TAB2	Mercury	TAB2+7	Neptune
+1	Venus	+8	Pluto
+2	Earth	+9	Sun
+3	Mars	+10	Moon
+4	Jupiter	+11	Earth–Moon barycenter
+5	Saturn		
+6	Uranus	+12	Nutations

Table B-5. TAB4 structure

Word position	Contents
TAB4	Floating point control-word integer indicating type of error, if any
+1	Zero cell for double-precision compatability
+2	Mercury position and velocity in double-precision floating point
+14	11 more sub-blocks of position and velocity data for each of the other bodies in double-precision floating point, each sub-block consisting of 12 words, in the same order as given in TAB2
+146	Nutation in longitude and nutation in latitude in single-precision floating point
+148	Nutation rates in single-precision floating point

Table B-6. TAB4 error code interpretation

Control word	Meaning
0.	Successful return
1.	Specified date T_j smaller than starting date of data available
2.	T_j greater than final date of data available
3.	Reading error
4.	Some TAB2 control word is negative or greater than three
5.	CENTER control word is in error

and

NTAPE = location of a word containing a fixed-point number designating the logical tape unit on which the JPL Ephemeris Tape is mounted

IV. OUTPUT

The output from EPHEM consists of the contents of TAB4 as described in Part III. All data are expressed in the equatorial reference system of the mean equator and equinox of 1950.0.

V. RESTRICTIONS

EPHEM makes extensive use of IBM 7094 double-precision instructions. Therefore, all tables provided by the user must start at even locations in core.

EPHEM considers all tables to be loaded from a low-order core toward a higher-order core. Users with programs written in the FORTRAN II system must be aware of this and set up tables accordingly.

The only other restrictions are those imposed by the FORTRAN II monitor system.

APPENDIX C

Document Description

Each of the source, position–velocity, and JPL Ephemeris Tapes is accompanied by a document describing the data. The document describing any particular set of JPL Ephemeris Tapes is a JPL Technical Memorandum and is distributed as part of the JPL Ephemeris Tape Package. Its contents are compiled from the documents describing the position–velocity tapes from which the particular set of JPL Ephemeris Tapes was obtained.

The source and position–velocity tape documents are on standard forms, which are illustrated in this Appendix. The documents, which are for internal use only, are called IDIOT's, for Identification Document, Internal Only, Tape.

The information on source tape documents is as follows:

1. Name of body for which data are supplied and tape number
2. The 24 BCD words that make up the first record of the data tape
3. Coordinate system in which data are expressed. This will necessarily include the central body.
4. Units in which data are expressed
5. The Julian dates covered by the data and the data step size
6. Source of ephemeris data
7. Theory from which generated
8. Corrections to theory, if any
9. Accuracy of data

and

10. Checks performed on data

The information on position–velocity tape documents is as follows:

1. Name of body for which data are provided and tape number
2. The 24 BCD words that make up the first record of the data tape
3. Coordinate system in which data are expressed. This will necessarily include the central body.
4. Units in which data are expressed
5. The Julian dates covered by the data and the data step size
6. Fit program used
   a. PLOD 1
   b. PLOD 2
   c. Other
7. Units of velocity
8. Reference number of IDIOT describing source tape from which generated
9. Document reference for source data

and

10. Statistical summary page for PLOD-generated tapes